Analysis and Evaluation of the Performance of the TOPSAR Topographic SAR Interferometer

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Abstract

Across-track interferometric SAR provides high resolution both horizontally and vertically which is of importance to topographic mapping applications. 'The accuracy of the derived Digital Elevation Model (DEM) is determined by factors such as data acquisition geometry, signal-to-noise ratio, knowledge of platform position and attitude as well as the accuracy of the processing system.

In the summer of 1992 we acquired TOPSAR over the Ft. Irwin area in California, a desert area with significant relief (height standard deviation 150 m). Very accurate DEMs have been derived for this area by the Topographic Engineering Center (TEC) using digital correlation methods on 1:20,000 scale digitized photographs. Corner reflectors were deployed in the area, and their locations were determined to cm accuracies by the Defense Mapping Agency (DMA) using differential GPS techniques.

DEMs generated from the acquired radar data has been rotated and translated to overlay the reference DEMs provided by TEC. A detailed description of the errors and their characteristics will be given. The standard deviation measured over a 5.6 by 7 km area was 3.0 m, the corresponding figure for a relatively flat 2.8 by 3.4 km area was 1.25 m.

We will also discuss key factors that presently limit the system performance and conclude with a description of current research in this area.

ANALYSIS AND EVALUATION OF THE PERFORMANCE OF THE TOPSAR INTERFEROMETER

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TOPSAR Evaluation Experiments 1991

- Across-track interferometric SAR data were acquired over Ft. Irwin, California, and Walnut Gulch near Tombstone, Arizona.

- Radar derived rectified height maps were generated using an integrated processor including SAR processing, interferometric processing, and geometric rectification

- Ft. Irwin data were evaluated by comparison to a USGS DEM with 30 m horizontal pixel spacing and 7 m vertical accuracy. The resulting difference map had a 5.5 m standard deviation

- Walnut Gulch data were evaluated by comparison to a DEM provided by the U.S. Agricultural Department. This DEM had a 40 m horizontal pixel spacing and a photogrammetric accuracy of 0.5 m. Some errors in the reference were apparent. The resulting difference map had a 3.6 m standard deviation

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THE FT. IRWIN NATIONAL TRAINING CENTER EXPERIMENT 1992

- Sponsored by DARPA JPL collected data over the Army National Training Center (NTC), Ft. Irwin, California on July 8th, 1992
- 3 TOPSAR data sets were acquired. Two east-west opposite side mapping tracks, and one north to south track
- 10 corner reflectors deployed by JPL. Corner ref lectors surveyed by the Defense Mapping Agency (DMA) to centimeter accuracy using differential GPS
- Very accurate DEM developed by the Topographic Engineering Center (TEC) using digital correlation methods on 1:20,000 scale digitized photographs

ANALYSIS APPROACH

- Evaluation based on standard TOPSAR product (run 1 & run 3) with 10 m pixel spacing (5 m product is also available).

- Radar DEMs were co-registered to TEC DEM horizontally using corner reflectors. Azimuth, range scaling errors were determined and skew estimated.

- Vertical alignment were established using two different approaches:
  - by removing an azimuth slope, a range slope, and a height off-set based on corner reflector measurements
  - by removing azimuth, range slopes and height off-set that will match the TEC DEM in a least square error sense

- Height errors after re-sampling radar data to reference DEM were analyzed on a pixel to pixel basis. Mean, standard deviation, and . standard deviation after rejection of 50 values were measured

Horizontal Alignment Transformation

- **Transformation applied**

$$\begin{pmatrix} x \\ y \end{pmatrix}_{\mathrm{DEM}} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \gamma & 1 \end{pmatrix} \begin{pmatrix} \lambda_x & 0 \\ 0 & \lambda_y \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}_{\mathrm{TOPSAR}} + \begin{pmatrix} \delta x \\ \delta y \end{pmatrix}$$

- **Transformation parameters**

	RUN 1	RUN 3
Azimuth scale factor, λ_x	1.0033	0.9979
Range scale factor, λ_y	1.0025	1.0036
Skew [radians]	-2.2.10-4	$(-2.5\cdot 10^{-4})$
Rotation angle [degrees]	73.3	-16.8

- **NTC RUN 1 corner reflectors (4) consistent to 2.4 m in range and 0.8 m in azimuth**

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CORNER REFLECTOR BASED VERTICAL ALIGNMENT

	NTC RUN 1 Entire DEM	NTC RUN 3 Entire DEM
Azimuth tilt [mrad = m/km]	0.44	-0.27
Range tilt [mrad = m/km]	8.28	6.78
Horizontal off-set [m]	553.38	571.37
Std. deviation DEM	112.65	112.65
No. of Points	391891	389378
Std. deviation cliff. [m]	2.07	3.01
Mean cliff. [m]	-0.22	-1.40
5 sigma pts. rejected:		
#pts rejected	279	60
Std. deviation cliff. [m]	1.96	2.99

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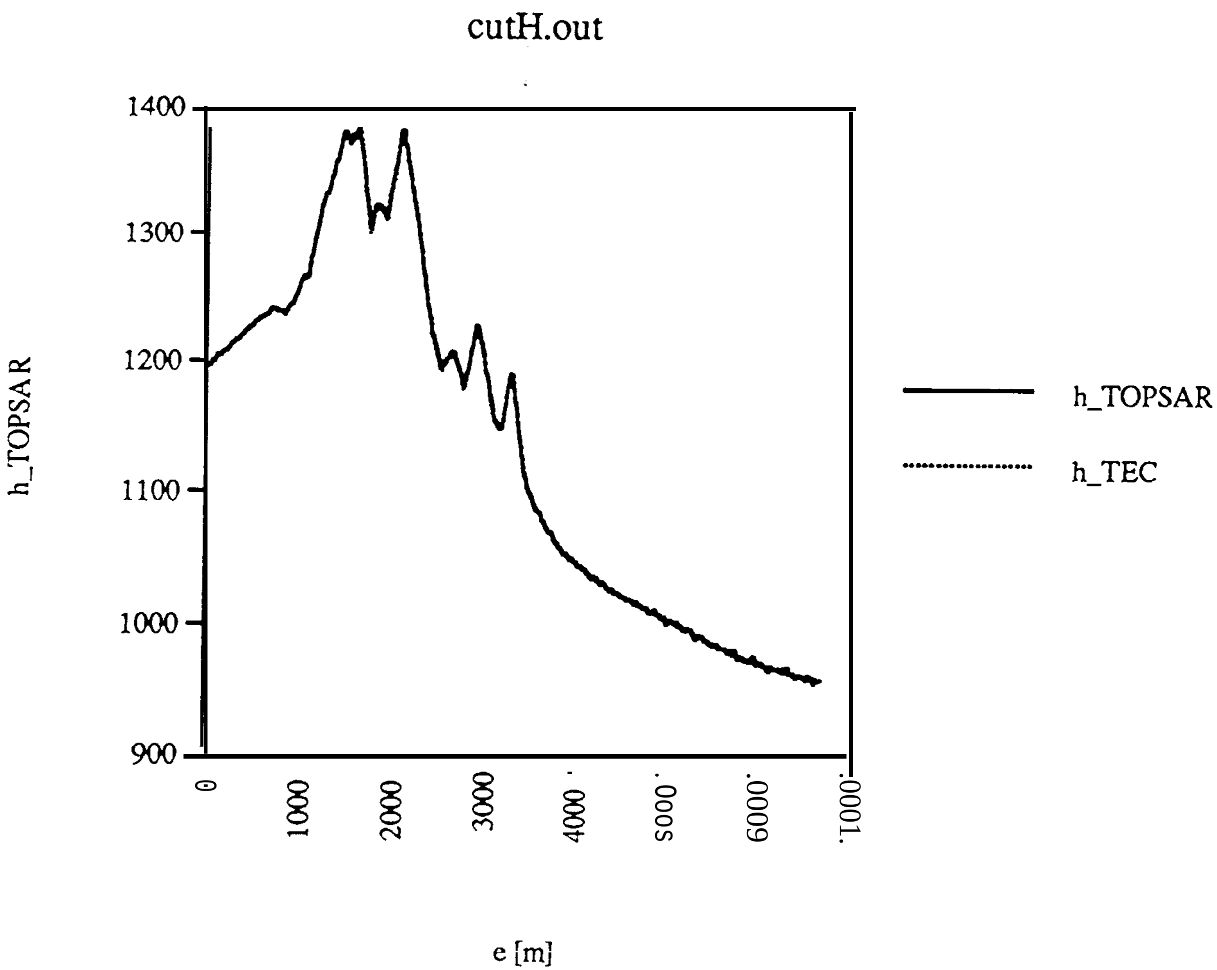
TEC DEM Based Vertical Alignment

NTC RUN 1	Entire DEM	Flat area	Mtn. area
Std. deviation DEM [m]	112.65	13.70	74.50
No. of Points	391891	10000	10000
Std. deviation cliff. [m]	1.89	1.06	3.31
Mean cliff. [m]	0.00	-0.40	130
5 sigma pts. rejected:			
#pts rejected	279	0	114
Std. deviation cliff. [m]	L76	1.06	2.25

NTC RUN 3	Entire DEM	Flat area	Mtn. area
Std. deviation DEM [m]	112.65	17.85	74.50
No. of Points	38937S	10000	10000
Std. deviation cliff. [m]	2.27	1.99	2.15
Mean cliff. [m]	0.00	-0.92	-0.29
5 sigma pts. rejected			
#pts rejected	228	0	16
Std. deviation cliff. [m]	2.23	1.99	2.02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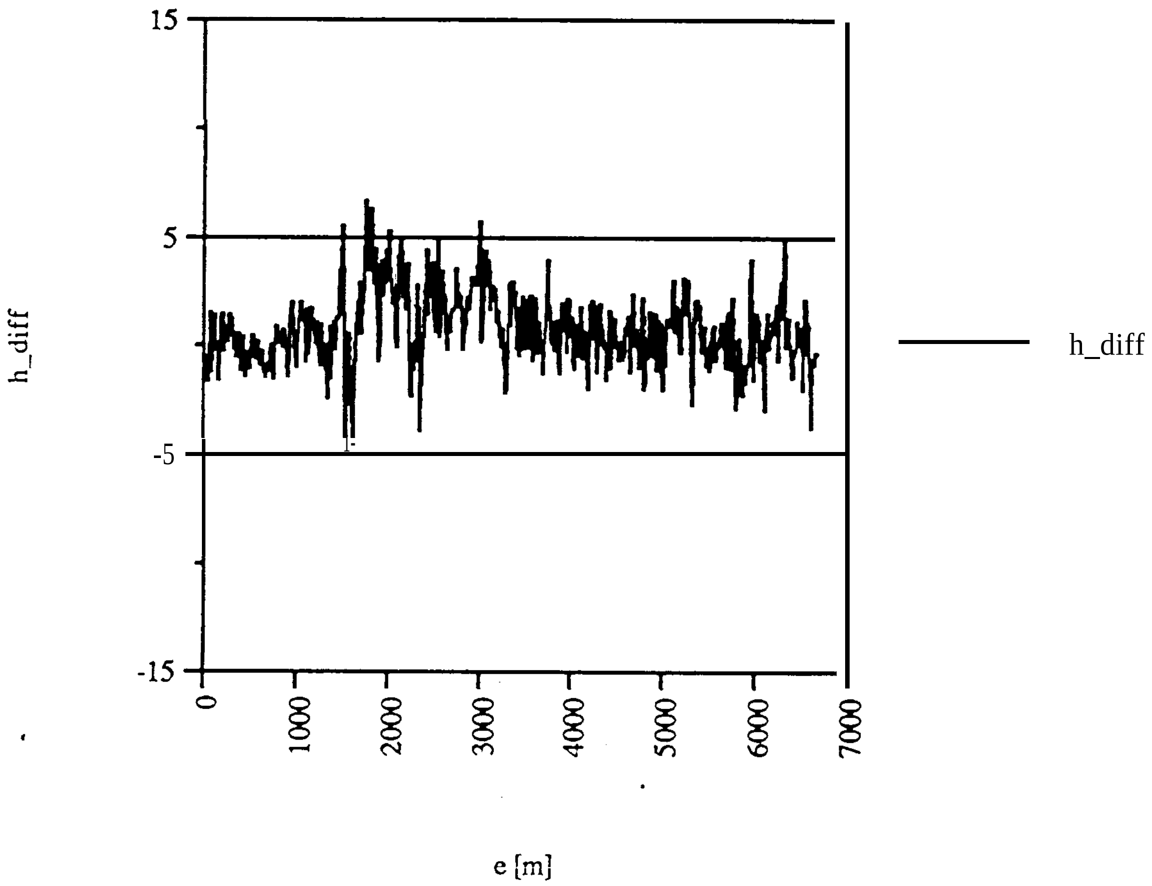

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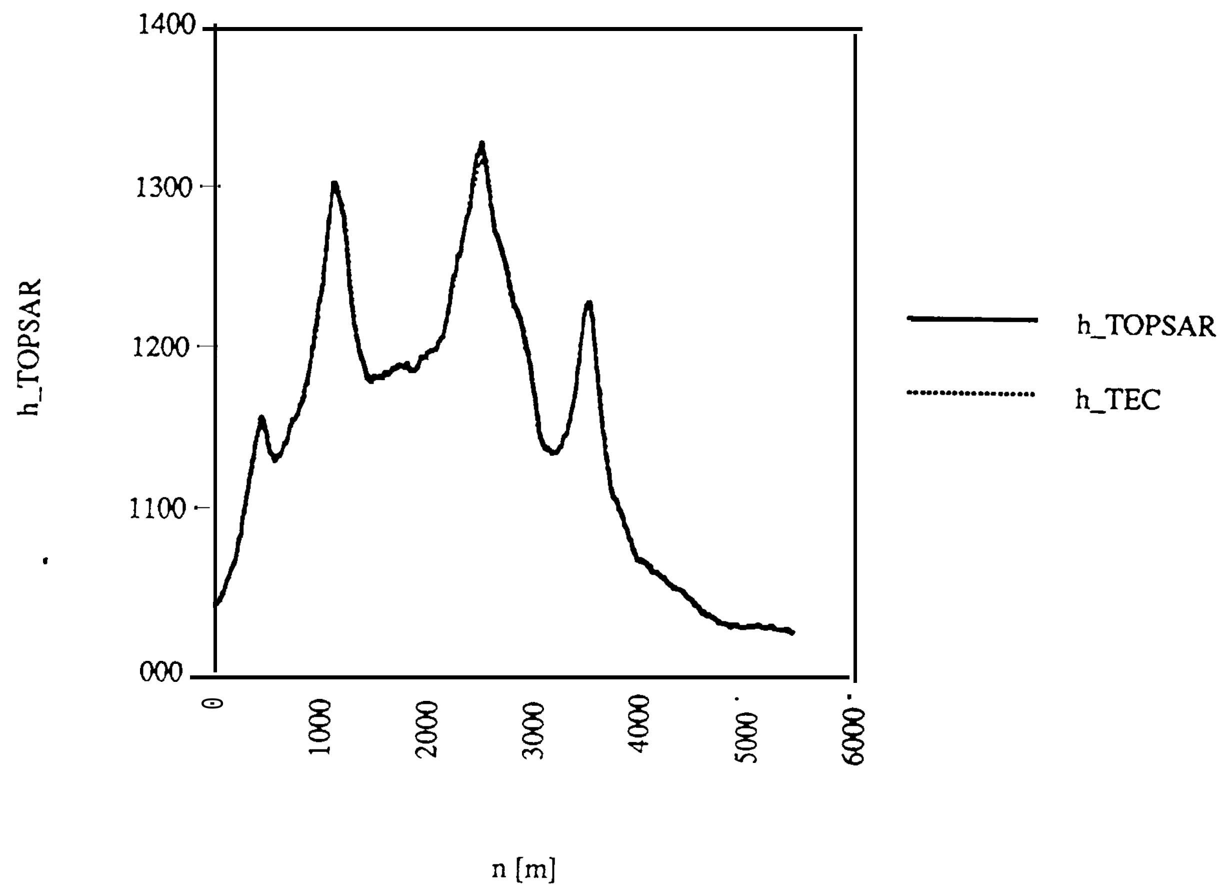
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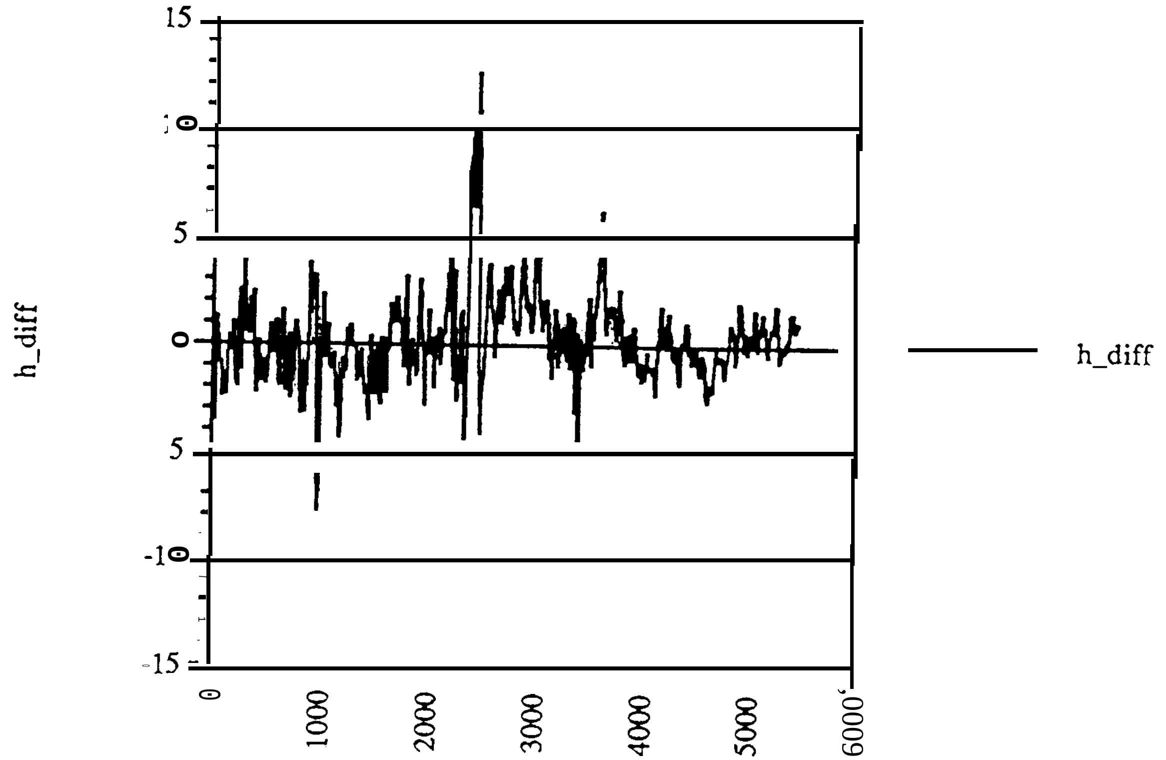

JPL's TOPSAR ELEVATION DATA COMPARED TO TEC'S DEM (NTC)

JPL's FILE 1

	RAW DATA	ADJUSTED FOR SLOPE ERROR	IGNORE ERRORS > 5 SIGMA	FLAT AREA	MTN AREA
NO PTS	391760	*	(-882)	77700	54400
MEDIAN	2.4m	*	1.7m	1.3m	2.2m
RMSE	3.3m	*	2.3m	1.5m	3.0m
RANGE	-28/+58m	-26/+59m	-12/+12m	-6/+5m	-17/+25m
AVERAGE	-1.3m	0	0	-0.8m	-0.7m
SIGMA	3.0m	2.4m	2.3m	1.3m	2.9m

JPL's FILE 3

	RAW DATA	ADJUSTED FOR SLOPE ERROR	IGNORE ERRORS > 5 SIGMA	FLAT AREA	MTN AREA
NO PTS	398 000	*	(-346)	77700	54400
MEDIAN	9.2m	*	1.9m	1.9m	2.7m
RMSE	10.7m	*	2.5m	2.4m	3.7m
RANGE	-37/+35m	-31/+31m	-13/+13m	-11/+12m	-20/+31m
AVERAGE	-4.2m	0	0	+0.1m	+0.3m
SIGMA	9.8m	2.6m	2.5m	2.4m	3.7m

"RAW DATA" . . . . . .Original elevations in overlap area rotated to WGS84 UTM system.
"ADJUSTED". . . . . . .Raw Data transformed (leveled) by dz = ax + by + c.
"5-SIGMA . . . . .Adjusted data without errors exceeding 5 times the sigma error.
"FLAT AREA" . . . . .A subset of the adjusted data was extracted from the flat area.
"MTN AREA". . . . . .A subset of the adjusted data was extracted from the mountainous area.
' FILE 1 slopes 0.8m per 1000m East, 0.2m per 1000m North.
' File 3 slopes 5.8m per 1000m East, 2.0m per 1000m North

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ERRORS• URCES

Horizontal position errors:	Error Sources:
- Azimuth scale	Velocity bias (nav. system)
- Range scale	Baseline length
	Absolute phase ambiguity
	Slant range calibration
– Skew	velocity bias, processor
- Rubber sheet distortion	Mocomp = Nav. + Processor
– High frequency across-track	Signal-to-noise-ratio
	Impulse response (ISLR etc.)
	Channel co-registration

ERROR SOURCES (2)

Vertical errors:	Error Sources:
- Azimuth tilt	Vertical velocity bias
- Range tilt	Attitude bias (in particular) Baseline orientation Absolute phase ambiguity
- Vertical off-set	Nav. system position
– Correlated height error	Mocomp = Nav. + Processor Multi-path Quantization correlation
– High frequency random	Signal-to-noise-ratio Impulse response (ISLR etc.) Channel co-registration

DISCUSSION

- Horizontal resolution, and accuracy requirements:
  - Registration errors on the order of 2 to 5 meter have been found to have a significant impact on the measured DEM error
  - [n rough terrain the horizontal positioning accuracy must be approximately equal to the required vertical DEM accuracy. Horizontal resolution is probably less critical by a factor 2–3
  - Processor interpolation and regrinding algorithms are critical!

- Absolute accuracy requirements:
  - Will additionally require state-of-the-art position, velocity and attitude; motion compensation processing, and atmospheric corrections

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DISCUSSION (2)

- Test/evaluation procedures and experiments:
  - IF-SAR potential for topographic mapping can only be assessed by carefully designed experiments
  - Sensor system effects must be studied separately from target interaction effects (volume scattering)
  - Rough terrain with little or no vegetation is well suited for sensor system evaluation
  - State-of-the-art reference DEMs are required

- Calibration
  - Many parameters to calibrate. Several of them give correlated errors
  - More work required on designing calibration procedures that will determine individual parameters